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CROPGRO-Cotton model for determining climate change impacts on yield, water- and N- use efficiencies of cotton in the Dry Savanna of West Africa

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ABSTRACT

Cotton is an important cash crop in many West African countries. Hence, its sustainable production will support the national economies as well as the livelihoods of the farming population alike and in turn help easing widespread poverty. However, future climate change may affect the productivity of cotton in West Africa. Therefore, the objectives of this study were to (i) parameterize the Cropping System Model- CROPGRO-Cotton to simulate growth, seed cotton yield, and in-season soil water dynamics and nitrogen (N) uptake, and (ii) apply the model to estimate potential climate change impacts on cotton growth, yields, and water- and N- productivity under different soil-fertility management practices. The CROPGRO-Cotton model was first parameterized and evaluated using datasets collected in three field experiments conducted in 2014 and 2015 in the Dry Savanna of northern Benin, West Africa. The model was next applied to determine long-term responses of cotton to historical (1986–2015) and projected climate (2080–2099) for three Representative Concentration Pathways (RCPs 2.6, 4.5, and 8.5). CROPGRO-Cotton accurately simulated in-season soil water dynamics (nRMSE of 12–27%, d-values of 0.79–0.88), N uptake (nRMSE of 31–44%, d-values of 0.89–0.96), and biomass accrual (nRMSE of 31–46% and d-values of 0.91–0.97), as well as seed cotton yield at harvest (nRMSE of 24–39% and d-value of about 0.81). The model predicted higher seed cotton yield with planting dates in June compared to July. Under the climate change scenario of RCP2.6, CROPGRO-Cotton predicted a decrease in water use efficiency (WUE) by 20% without any soil amendment, and by 4% with an integrated soil-crop management compared to the historical run, but an increase of 2% with a high use of mineral fertilizer. With the RCP4.5 and 8.5 scenarios, the predicted changes in WUE varied between −1% and 17% across the soil fertility management options. CROPGRO-Cotton predicted increases in N-partial factor productivity by 7 to 31%. The N uptake varied between −7% and 46% whilst seed cotton yield varied between −7 and 41%. The findings underlined that the predicted future increases in water and N productivity in cotton will be driven by CO_2 fertilization, increases in temperatures as well as rainfall variability, but at the expense of soil fertility leading to soil mining. Yet, even if cotton, unlike some other crops in the region, will likely respond positively to climate change, adequate soil fertility management practices are essential to ensure efficient and sustainable water- and N- use in the expected future.

1. Introduction

Cotton (*Gossypium hirsutum* L.*)* plays an important role in social and economic development not only in the world, but also in various West African countries. To this end, its sustainable production will support livelihoods of the farming population and help easing wide-spread poverty. Cotton production in West and central African countries such as Benin, Burkina Faso, Mali, Ivory Coast, Togo, and Chad accounts for 5% of the world production (Hussein et al., 2006), representing 2–10% of the Gross Domestic Product (GDP), and 30–56% of total exports of these countries (Hussein et al., 2006; Vitale et al., 2011).

Cotton production systems are considered typical examples of crop intensification in West Africa (Pieri, 1992). This was consequent to considerable investments in soil fertility restoration and agricultural land expansion that temporarily resulted in seed cotton productivity improvement (Vitale et al., 2011). Subsequent staple crops like maize

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(*Zea mays* L.), sorghum (*Sorghum bicolor* L.), or millet (*Pennisetum glaucum* L.) often benefitted from the inputs of cotton cultivation (Ripoche et al., 2015; Vitale et al., 2009). Yet, even though the intensification of cotton production has undeniably increased cotton yields in the past decades in West Africa (Pieri, 1992; Theriault and Tschirley, 2014), this progress has stagnated or even declined, due to the increased costs of inputs without a compensation in the seed cotton prices (Baquedano et al., 2010) as well as due to biotic and abiotic-stresses (Sultan et al., 2010). Moreover, the performance of the current cotton cropping systems is challenged by rainfall variability and drought (Sultan et al., 2010), declining soil fertility (Bationo et al., 2012; Pieri, 1992; Vitale et al., 2009), and suboptimal soil-crop management such as late planting (Lançon et al., 2007; Lançon et al., 1989). Sustainable cotton production practices and systems are needed if this commodity is to maintain its key role in the overall national and regional economy and to secure further the livelihoods of farmers in West Africa. Measures to be introduced must enhance productivity and increase the resilience of the farming systems without compromising the environment.

Changes in the biogeochemical cycle of carbon through atmospheric carbon dioxide enrichments (IPCC, 2013) and climate change, especially changes in rainfall (Gbobaniyi et al., 2014; Sylla et al., 2013) and increasing temperatures (Dike et al., 2015; Riede et al., 2016), are expected to drive changes in cotton production (Gérardeaux et al., 2013; Reddy et al., 2002). The role of N-fertilization is reportedly affected by these changes, particularly by CO_2 enrichment (Prior et al., 1998; Singh et al., 2013). However, little is known about the extent to which cotton will respond to soil fertility management options under the climate changes and variability as predicted for West African Dry Savanna environments.

Crop simulation models are valuable tools to quantify responses in cotton yields and resource use efficiency to different soil fertility management strategies. Previous studies investigated cotton productivity with cotton-specific models such as GOSSYM (Baker et al., 1983), Cotton2K (Marani, 2004), COTCO2 (Wall et al., 1994), OZCOT (Hearn, 1994), and CROPGRO-Cotton (Hoogenboom et al., 2015; Jones et al., 2003). Likewise, generic crop models like EPIC, WOFOST, SUCROS, GRAMI, Cropsysts, and Aquacrop have been used to simulate cotton production (Thorp et al., 2014a). CROPGRO-Cotton has been widely applied for assessing soil fertility and water management options (Garcia y Garcia et al., 2010; Modala et al., 2015; Paz et al., 2012; Wajid et al., 2014) or the impacts of climate change on cotton production (Adhikari et al., 2016; Gérardeaux et al., 2013; Thorp et al., 2014b). However, little, if at all, has been reported about the evaluation and application of CROPGRO-Cotton for assessing climate change impacts on resource use efficiency in West Africa. The objectives therefore were to (i) parameterize the Cropping System Model- CROPGRO-Cotton to simulate growth, seed cotton yield, and in-season soil water dynamics and nitrogen (N) uptake, and (ii) apply the model to estimate potential climate change impacts on cotton growth, yields, and water- and N- productivity under different soil-fertility management practices in the Dry Savanna of northern Benin, West Africa.

2. Materials and methods

2.1. Description of CROPGRO-Cotton model

CROPGRO-Cotton simulates growth, development, and yields of cotton in response to soil, weather, and management conditions and combinations thereof (Hoogenboom et al., 2015; Thorp et al., 2014b). The model computes biophysical processes on a daily time step routine (Jones et al., 2003). The growth stages (i.e. crop development) are based on photo-thermal time. CROPGRO-Cotton simulates carbon assimilation and the partitioning of biomass into roots, stems, leaves, and bolls (Thorp et al., 2014a). The canopy photosynthesis is computed using leaf-level photosynthesis parameters and the hedgerow light interception (Boote et al., 1998), while yield components are derived from boll mass, seed cotton mass, seed number, and unit seed weight (Thorp et al., 2014a). CROPGRO-Cotton can hence account for stress effects from soil water and nitrogen deficits (Thorp et al., 2014b), as well as air temperature (Thorp et al., 2014a) on cotton growth and development. CROPGRO-Cotton integrates effects of atmospheric carbon dioxide (CO_2) on photosynthesis and transpiration (Thorp et al., 2014a), computes evapotranspiration (Boote et al., 1998), and simulates soil carbon, nitrogen (Gijsman et al., 2002; Godwin and Singh, 1998) and water balances (Ritchie, 1998).

2.2. Field experiments and datasets

The datasets needed for the initial calibration and evaluation of CROPGRO-Cotton were collected from three field experiments conducted on Alisols, Plinthosols, and Luvisols (IUSS Working Group WRB, 2014; Steup, 2016) in 2014 and 2015 at Ouri-Yori village (10°49′1″N, 1°4′7″E) located in North Benin, West Africa. The experimental area experiences a dry savanna type of climate, with total annual rainfall from May to October amounting to 1099.5 ± 195.8 mm over 1986–2015. The annual mean minimum temperature, maximum temperature, and solar radiation for the same historical period were 21.4 ± 0.6 °C, 33.7 ± 0.7 °C, and 19.5 ± 0.5 MJ m^{-2} d^{-1}, respectively (Amouzou et al., 2018a). During the experimental period, the total annual rainfall amounted to 937 mm in 2014 and 1096 mm in 2015. However, during the growing cycle of cotton rainfall amounted to 639 mm in 2014 and 956 mm in 2015. The average minimum temperature and maximum temperature during cotton growing were 23.9 and 34.2 °C in 2014 and 22.9 and 31.9 °C in 2015, respectively. From planting to the harvest of cotton, the average solar radiation was 18.7 MJ m^{-2} d^{-1} in 2014 and 19.3 MJ m^{-2} d^{-1}.

Experiment-1, an on-farm researcher-managed trial, involved a high use of mineral fertilizer, which was almost two times the recommended rate: 80 kg N ha^{-1}, 26 kg P ha^{-1}, 30 kg K ha^{-1}, 7.5 kg S ha^{-1}, and 0.25 kg B ha^{-1}. This treatment was selected to ensure nutrient-stress-free conditions, needed to collect the data for the initial calibration and validation of the CROPGRO-Cotton model. Experiments-2 and 3 were purposefully designed to collect the datasets essential for evaluating the robustness of the model after parameterization. Experiment-2, therefore, was designed as an on-farm, researcher-managed trial with an unamended soil (no fertilization) and an integrated soil-crop management component (recommended fertilizer rates, 44 kg N ha^{-1}, 15 kg P ha^{-1}, and 17.5 kg K ha^{-1}, 7.5 kg S ha^{-1}, and 0.25 kg B ha^{-1}, with crop residue retention) as treatments. Experiment-3, an on-farm farmer-managed trial, was designed to capture cotton responses under farmers' management practices. The experimental factors and design, as well as crop and soil management, were previously described in detail for each experiment (Amouzou et al., 2018a). Each of the three experiments included maize, sorghum, and cotton as test crops (Appendix A), but only data for the cotton-based treatments were considered here. The experiments-2 and 3 were rainfed in both years, although experiment-2 was re-designed in 2015 to include supplementary irrigation as an additional factor.

Cotton phenology (e.g. anthesis and physiological maturity monitored as days after planting (DAP)), biomass accrual, final biomass and seed cotton yields were collected in experiment-1. In experiment-2, in-season biomass growth, soil water, and N uptake, as well as final biomass and seed cotton yields were measured. Biomass and seed cotton yields at final harvest were collected in experiment-3 also. Additional details on the methods, measurements and processing of soil and plant samples were previously reported (Amouzou et al., 2018a, 2018b).

2.3. Model input data sets

Initial soil profile data for the three different soils and weather data for the 2014 and 2015 growing seasons were obtained from Steup

Table 1
Physical and chemical characteristics of the soils at the experimental sites and used for calibrating and evaluating the CROPGRO-Cotton model.

Soil	Layer (cm)	pH	Org. C (%)	Total N (%)	Bray 1P (ppm)	CEC Cmol (+) kg^{-1}	Sand (%)	Silt (%)	Clay (%)	Bulk density (gcm^{-3})
Gleyic Alisols	20	5.9	0.28	0.05	1.0	6.2	82.4	15.2	2.5	1.4
	40	6.1	0.14	0.04	1.0	7.8	82.1	12.8	5	1.4
	60	5.9	0.13	0.06	1.0	5.8	79.4	10.7	10.9	1.4
Dystric Plinthosols	20	6.5	0.70	0.09	3.0	6.4	75.0	19.9	4.0	1.5
	40	6.8	0.18	0.06	1.0	8.6	77.2	19.4	4.5	1.5
	60	7.0	0.17	0.05	2.0	7.2	63.9	26.4	10.8	1.4
Ferric Luvisols	20	6.6	0.68	0.08	4.0	8.5	68.7	21.1	4.8	1.5
	40	6.4	0.31	0.06	3.0	4.6	63.1	29.3	9.3	1.5
	60	6.5	0.23	0.06	1.0	8.7	27.9	32.9	31.2	1.5

Source: Datasets from Steup (2016).

(2016). Soil physical and chemical characteristics (Table 1) as well as weather data were previously reported (Amouzou et al., 2018a, 2018b). The CROPGRO-Cotton inputs files were prepared using the appropriate tools in DSSAT-CSM v.4.6, SBuild utility program for initial soil input, Weatherman for weather data, XBuild for cotton management data, and AT Create for system performance datasets.

2.4. Model calibration

The CROPGRO-Cotton model was calibrated using empirical data on growth, development and yields from experiment-1 in 2014. The independent measurements in 2015 from the same experiment were used to validate the parameterized model.

The locally improved cotton variety H-279-1 was parameterized by adjusting manually various genetic coefficients to get an accurate goodness of fit between simulated and measured values in the absence of water and N deficits. Cotton cv. Deltapine 555, the default in DSSAT-CSM, was used as the starting cultivar for calibration. Key phenological traits such as critical short day length (CSDL) and photo-thermal days from emergence to flower appearance (EM-FL) were adjusted to match the observed anthesis date. The default photo-thermal days from first seed to physiological maturity (SD-PM) were modified to match simulated with observed physiological maturity date. Next, the maximum leaf photosynthesis rate (LFMAX), photo-thermal days for seed filling duration for pod cohort (SFDUR), maximum fraction of daily growth partitioned to seed + shell (XFRT), and maximum size of full leaf (SIZLF), maximum weight per seed (WTRSD), and threshing percentage (THRSH) were optimized for final seed cotton and biomass yields (Table 2). The soil fertility factor (SLPF) was optimized during the calibration of aboveground biomass and seed cotton yield.

The validated CROPGRO model was evaluated using the empirical data sets from experiments-2 and 3, without a modification of the genetic coefficients, but using the SLPF values and soil water-holding characteristics as previously reported for the different sites (Amouzou et al., 2018b).

2.5. Climate change and soil fertility management scenarios

Future climate parameters were estimated through ensemble mean predictions of three bias-corrected Global Circulation Models (GCMs: BNU-ESM, CanESM2, and MPI-ESM-MR) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) for three Representative Concentration Pathways (RCPs 2.6, 4.5, and 8.5) of the International Panel on Climate Change (IPCC, 2013). The RCP 2.6 is a low level Greenhouse Gases (GHG) forcing scenario (van Vuuren et al., 2011), RCP 4.5 a medium pathway (Thomson et al., 2011), and RCP 8.5 the rising GHG pathway (Riahi et al., 2011).

The bias-corrected data were obtained from the CGIAR- Program on Climate Change Agriculture and Food Security (CCAFS, 2017) for the baseline (1986–2005) and future climate (2080–2099). Three climate models were selected among the 21 GCM available, i.e. BNU-ESM of the College of Global Change and Earth System Science, Beijing Normal University (Ji et al., 2014), CanESM2 of the Canadian Center for Climate Modeling and Analysis (Chylek et al., 2011), and MPI-ESM-MR of the Max Plank Institute for Meteorology (Jungclaus et al., 2010). The selection of these models was guided by the highest correlations

Table 2
Default genetic coefficients of cotton cv. Deltapine 555 used during calibration and the adjusted coefficients for cotton cv. H-279-1 used during validation and evaluation of CROPGRO-Cotton.

Codes	Definitions	*Gossypium hirsutum*	
		Default values Deltapine 555	Calibrated H-279-1
CSDL	Critical Short Day Length below which reproductive development progresses with no day length effect (hour)	23	12.5
PPSEN	Slope of the relative response of development to photoperiod with time (1/h)	0.1	0.1
EM-FL	Photo-thermal days between plant emergence and flower appearance	38	39
FL-SH	Photo-thermal days between first flower and first pod	11	11
FL-SD	Photo-thermal days between first flower and first seed	16	16
SD-PM	Photo-thermal days between first seed and physiological maturity	43	48
FL-LF	Photo-thermal days between first flower and end of leaf expansion	65	65
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO_2, and high light(mg $CO_2/m^2/s$)	1.1	3
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2/g)	170	170
SIZLF	Maximum size of full leaf (cm^2)	300	350
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.76	0.72
WTPSD	Maximum weight per seed (g)	0.18	0.1
SFDUR	Photo-thermal days for seed filling duration for pod cohort	35	30
SDPDV	Average seed per pod (n./pod)	27	27
PODUR	Photo-thermal days required to reach final pod load	12	12
THRSH	Threshing percentage	70	85
SDPRO	Fraction protein in seeds	0.153	0.153
SDLIP	Fraction oil in seeds	0.120	0.120

between historical projections and observations, as well as a realistic representation of the seasonal rainfall cycle with the lowest deviations in rainfall, temperatures, and solar radiation. Daily outputs of these three models were calibrated using historical (1986–2005) datasets as observed by a weather station nearest to the experimental sites and bias corrected using the "delta" (change factor), "nudging" (bias correction), and quantile mapping approaches (Gudmundsson et al., 2012; Hawkins et al., 2013). Daily rainfall, minimum and maximum temperatures, as well as solar radiation for the baseline and future climate scenarios served as inputs to the CROPGRO-Cotton model to predict climate change impacts. The ensemble of the climate models predicted seasonal rainfall variability reaching −2% ± 6, −4% ± 8, and 1% ± 9 in that order for the RCP2.6, 4.5, and 8.5 scenarios. Changes in temperature under RCP2.6, 4.5, and 8.5 depicted increasing warming trends in minimum temperature (1.0 ± 0.2, 2.0 ± 0.2, 4.7 °C ± 0.4) and maximum temperature (1.1 ± 0.2, 2.0 ± 0.3, 4.6 °C ± 0.5). The climate models simulated a decrease in solar radiation (MJ $m^{-2}d^{-1}$) by −0.4 ± 0.2, −0.3 ± 0.2, and − 0.5 ± 0.2 for RCP2.6, 4.5, and 8.5, respectively.

Soil fertility management scenarios included the three soil fertility management options described above (Section 2.2).

2.6. Assessment of model performance

During model calibration and evaluation, the goodness of fit between the predicted and measured values was assessed using the root mean square error (RMSE), normalized-RMSE (nRMSE) (Yang et al., 2014), and Index of agreements (d) (Willmott, 1981). These statistics were computed using the following equations:

$$\mathrm{RMSE} = \left[\sum_{i=1}^{N} \frac{(Yi - Xi)^2}{N}\right]^{1/2} \quad (1)$$

$$\mathrm{nRMSE} = \frac{\mathrm{RMSE}}{\overline{X}} * 100 \quad (2)$$

$$\mathrm{d} = 1 - \frac{\sum_{i=1}^{N} (Yi - Xi)^2}{\sum_{i=1}^{N} (|(Yi - \overline{X})| + |Xi - \overline{Y}|)^2} \quad (3)$$

where N is the number of observations, Yi is the predicted value for the ith measurement and Xi is the observed value for the ith measurement; $\overline{Y}$ is the mean of the predicted values and $\overline{X}$ is the mean of the observed values.

2.7. Simulation of cotton seed yield responses to planting dates

To capture effects on cotton of an increasingly erratic onset of the growing season in the region (Ouorou Barre, 2014), seed cotton yield responses to different planting dates in the case study region were simulated while assuming the three soil fertility management options under Alisols for 20 years weather variability (1986–2005). Four planting dates (June 10th, June 25th, July 10th, and July 25th) were simulated using the seasonal analysis option in DSSAT V.4.6. With the tested cotton cultivar (H-279-1), "early" planting refers to planting between mid to late June and "late or delayed" planting to late July (Lançon et al., 1989; Sekloka et al., 2008).

2.8. Simulation of climate change impacts on growth, water- and N- use efficiencies

Climate change impacts were simulated using the historical and projected weather parameters as inputs to run the model in a seasonal mode for the three soil fertility management options while considering the planting date of June 25th (176, day-of-year (DOY)) on Alisols. The model outputs were evaluated using water use efficiency (WUE), N-partial productivity (N-PFP), and N- internal utilization efficiency (N-IE) as indicators for comparing predicted responses of cotton to each of the three soil fertility management options under historical climate (1986–2005) to the performance of the same options under future climate (2080–2099) for the RCPs 2.6, 4.5, and 8.5. The model outputs for WUE are expressed as seed cotton yield per unit of evapotranspiration [kg seed cotton (mm ET)$^{-1}$], N-IE by seed cotton yield per N uptake [kg seed cotton (kg N uptake)$^{-1}$], and N-PFP as seed cotton yield per N fertilizer applied [kg seed cotton (kg N fertilizer)$^{-1}$].

3. Results

3.1. Calibration and validation of CROPGRO-Cotton

Based on the empirical data from experiment-1 (2014), CROPGRO-Cotton simulated observed anthesis (50 ± 5 days after planting) and physiological maturity (121 ± 8 days after planting) accurately (RMSE (nRMSE) of 0 days (0%)). During validation, the calibrated model adequately predicted anthesis of cotton (51 ± 4 days after planting) and physiological maturity (126 ± 6 days after planting) with RMSE (nRMSE) of 2 days (4%) and 4 days (3%), respectively.

The CROPGRO-Cotton model predicted satisfactorily time series of aboveground biomass accumulation of cotton in 2014 (nRMSE of 32% and d-value of 0.94) and 2015 (nRMSE of 33% and d-value of 0.92). At final harvest in 2014, RMSE and nRMSE between measured (3408 ± 880 kg ha^{-1}) and simulated biomass yield were 128 kg ha^{-1} and 4%, respectively. The calibrated model predicted biomass yield (6144 ± 508 kg ha^{-1}) satisfactorily in 2015 (RMSE of 626 kg ha^{-1} and nRMSE of 10%). The CROPGRO-Cotton model simulated satisfactorily also the observed seed cotton yield of 1426 ± 350 kg ha^{-1} with RMSE of 254 kg ha^{-1} and nRMSE of 18%. Harvested seed cotton in experiment-1 amounted to 2373 ± 135 kg ha^{-1} in 2015, which was quite well predicted as evidenced by RMSE of 418 kg ha^{-1} and nRMSE of 18%.

3.2. Evaluation of CROPGRO-Cotton

3.2.1. In-season soil water dynamics

Based on the empirical data from experiment-2 in 2015, CROPGRO-Cotton reasonably simulated in-season soil moisture dynamics under rainfed (Fig. 1a–c) and supplementary irrigation (Fig. 1d, e) conditions. However, the model under-predicted soil moisture at 40–60 cm soil depth for the rainfed treatment up to approximately 90 DAP, but predicted soil moisture accurately thereafter until harvest (Fig. 1c). Under supplementary irrigated conditions, the model adequately simulated the observed soil moisture dynamics at 40–60 cm soil depth from 20 to 70 DAP, but under-predicted it thereafter (Fig. 1f).

3.2.2. In-season nitrogen uptake

The CROPGRO-Cotton model predicted N-uptake by cotton early in the season fairly well under both rainfed and supplementary irrigated systems with and without fertilization in experiment-2 (Fig. 2). Without fertilizer, the model predicted N-uptake accurately up to 50 DAP, but under-predicted it thereafter until harvest irrespective of water management (Fig. 2. A1, A3). For rainfed cotton with fertilizer application (Fig. 2 A2), the CROPGRO-Cotton model predicted N-uptake accurately up to 80 DAP, but over-predicted it thereafter. With fertilizer and supplementary irrigation (Fig. 2 A4), the model predicted satisfactorily N-uptake up to 50 DAP, but over-predicted it thereafter until harvest.

3.2.3. Aboveground biomass

The CROPGRO-Cotton model predicted early biomass accurately (up to 50 DAP) under rainfed and supplementary irrigation conditions irrespective of soil fertility management options. Thereafter, the model under-predicted the biomass accrual. The predictions of the model were most accurate for the treatments with fertilization (Fig. 3).

Under rainfed and supplementary irrigation conditions (experiment-

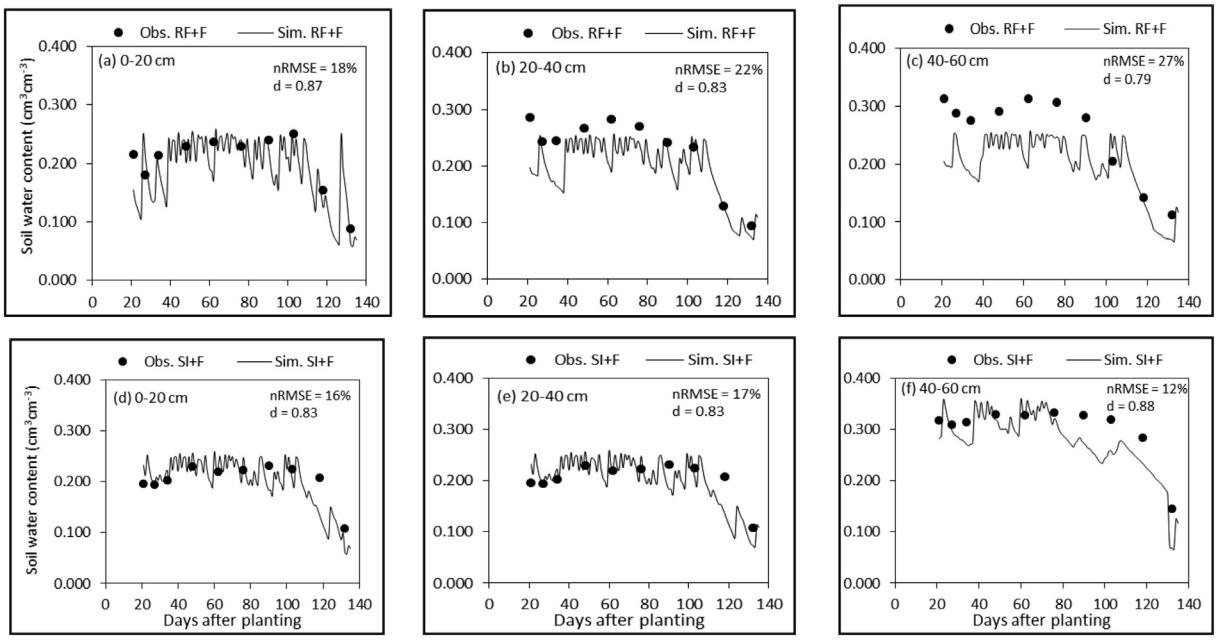

Fig. 1. Measured (symbols) and simulated (lines) soil water content at 0–20, 20–40, and 40–60 cm soil depth under cotton rainfed + fertilization (RF + F, a, b, c) and supplementary irrigation + fertilization (SI + F, d, e, f) conditions during the 2015 cropping season. (Findings from the researcher-managed experiment-2).

2) during 2014 and 2015, the model predicted with good accuracy biomass yield at final harvest as substantiated by nRMSE of 21% and d-value of 0.83 (Fig. 4a). Under farmer-management practices (experiment-3), the predictions (Fig. 4b) of the model were however more accurate (17% and 0.87 for nRMSE and d-value, respectively).

3.2.4. Seed cotton yield at harvest

The CROPGRO-Cotton model predicted reasonably well seed-cotton yield at harvest (Fig. 5a) as measured in experiment-2 (nRMSE (d-value) of 24% (0.82)). The accuracy of CROPGRO-cotton in predicting seed-cotton yield under farmer-managed conditions (experiment-3) was evidenced by nRMSE of 39% and d-value of 0.81 (Fig. 5b).

3.3. Long term simulation of seed cotton yield responses to planting dates and soil fertility management

The CROPGRO-Cotton model simulations showed that varying planting dates and soil fertility management options resulted in significant effects on seed cotton yield. The model performed well also in simulating the year-to-year variability of seed cotton yield for each planting date across the soil fertility management options (Fig. 6). The highest yields were simulated with planting date 161 DOY followed by planting date 176 DOY, irrespective of the soil fertility management option. However, seed cotton yield was highest with the use of mineral fertilizer (Fig. 6c) and the integrated soil-crop management practice (Fig. 6b) and lowest for the un-amended soil (Fig. 6a). The planting of

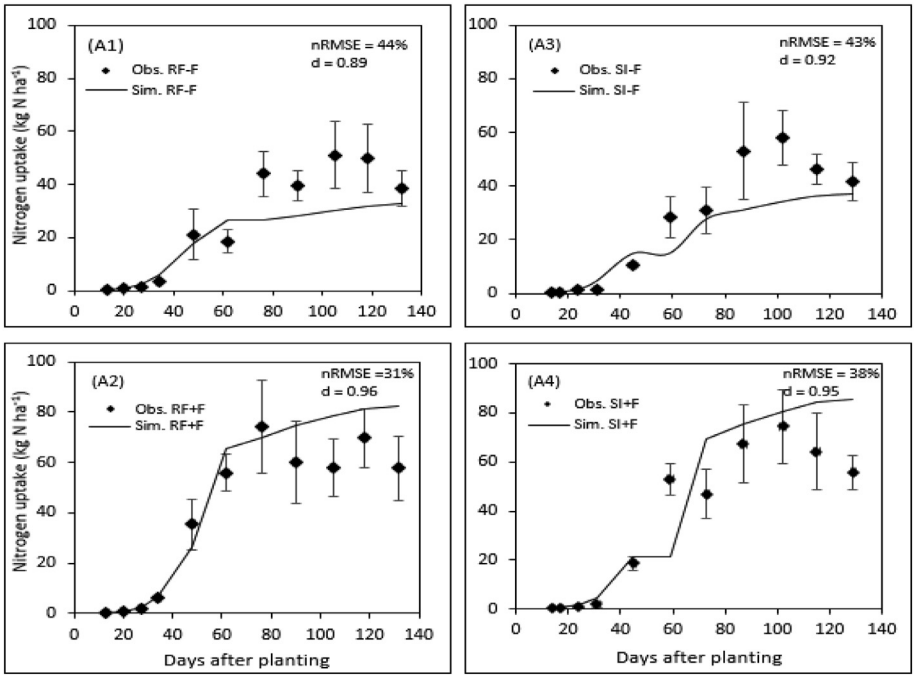

Fig. 2. Observed (symbols) and simulated (lines) nitrogen uptake of cotton under rainfed conditions without (RF-F, A1) and with fertilization (RF + F, A2), and supplementary irrigation without (SI-F, A3) and with fertilization (SI + F, A4) during the 2015 cropping season. (Findings from the researcher-managed experiment-2).

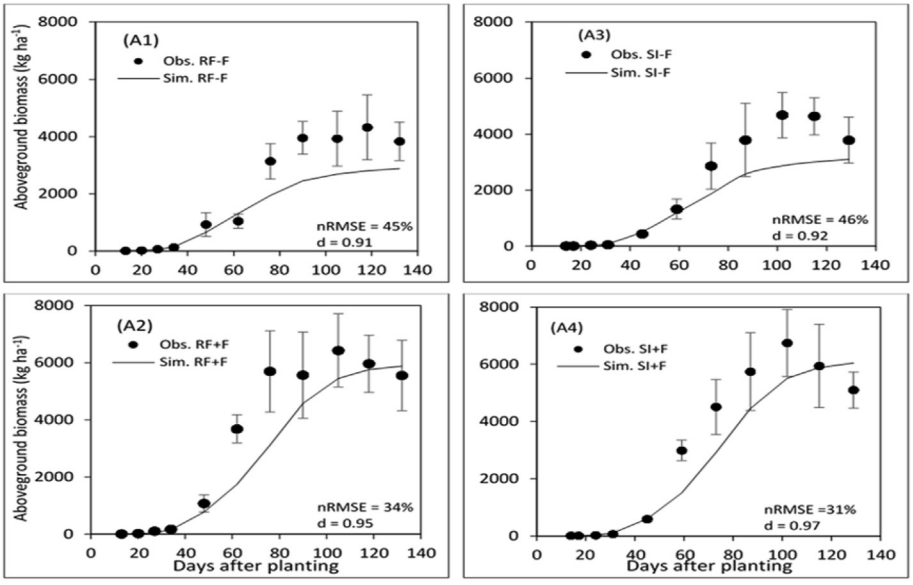

Fig. 3. Observed (symbols) and simulated (lines) changes in aboveground biomass of cotton under rainfed without (RF-F, A1) and with fertilization (RF + F, A2), and supplementary irrigation without (SI-F, A3) and with fertilization (SI + F, A4) during the 2015 cropping season. (Findings from the researcher-managed experiment-2).

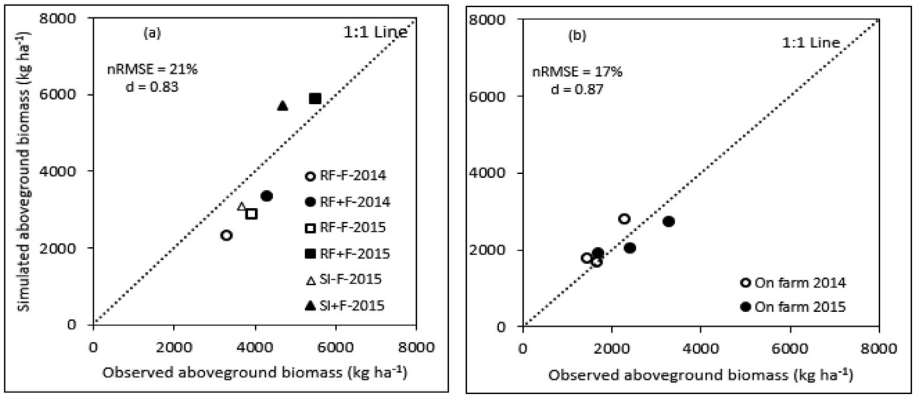

Fig. 4. Observed and simulated aboveground biomass of cotton at final harvest in the 2014 (open symbols) and 2015 (solid symbols) cropping seasons. (Findings from the researcher-managed experiment-2 (a) and farmer-managed experiment-3 (b)).

cotton from 191 DOY onwards decreased seed cotton yield substantially.

3.4. Climate change impacts on cotton

3.4.1. Changes in biomass accrual

The CROPGRO-Cotton model predicted increases in aboveground biomass accumulation of cotton under the projected climate change (2080–2099) relative to the historical means (1986–2005) irrespective of the soil fertility management options across the three climate scenarios (Fig. 7a, b, c), except for RCP 2.6 under the control (no-fertilization) (Fig. 7a). In the latter case, the model predicted a decrease starting from approximately 70 DAP onwards (Fig. 7a). The predicted increases in aboveground biomass growth of cotton peaked towards the

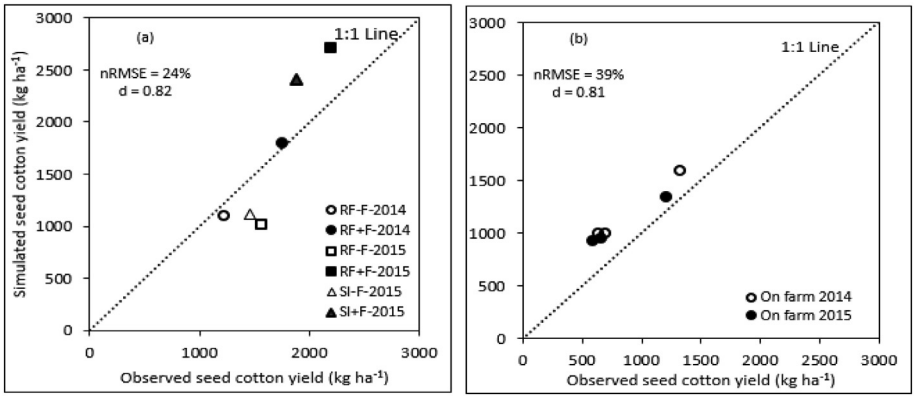

Fig. 5. Observed and simulated seed cotton yield of cotton at final harvest in the 2014 (open symbols) and 2015 (solid symbols) cropping seasons. (Findings from the researcher-managed experiment-2 (a) and farmer-managed experiment-3 (b)).

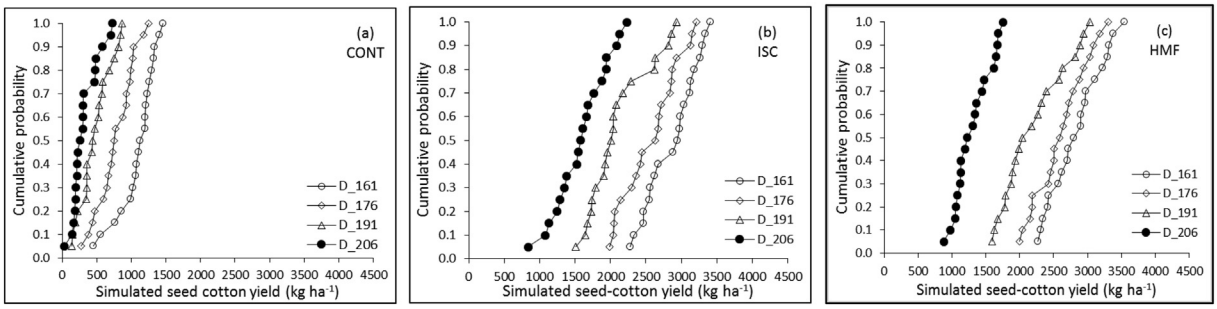

Fig. 6. Simulated seed cotton yield responses at 161 DOY (D_161), 176 DOY (D_176), 191 DOY (D_191), and 206 DOY (D_206) under un-amended soil (CONT), integrated soil-crop management (ISC), and high mineral fertilizer use (HMF) assuming the historical weather variability from 1986 to 2005. The DOY are assumed planting dates.

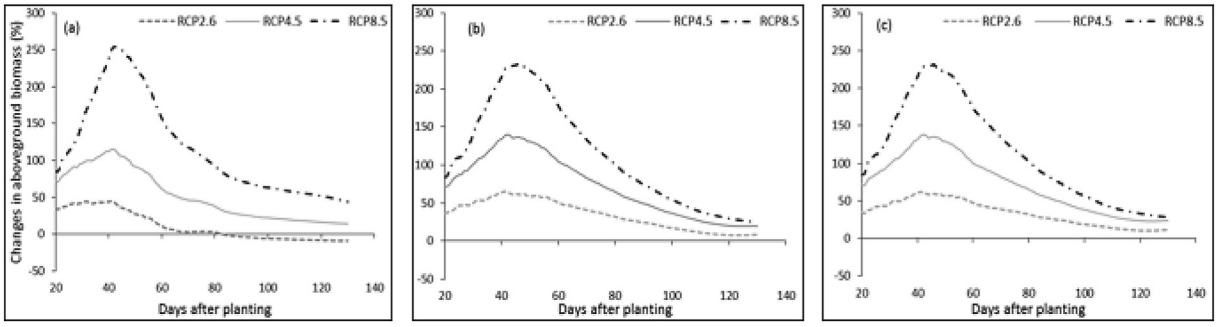

Fig. 7. Changes in cumulative aboveground biomass response of cotton under future climate (2080–2099) relative to their historical means (1986–2005) considering an un-amended soil as control (a), integrated soil-crop management (b), and high mineral fertilizer use (c) and while assuming three Representative Concentration Pathways of IPCC (RCPs 2.6, 4.5, and 8.5).

end of the vegetative growth (≈ 45 DAP) before declining sharply until harvest.

3.4.2. Changes in water- and N- use efficiencies

For the un-amended soil (CONT), CROPGRO-Cotton predicted an increase of 15% in cotton WUE under RCP8.5, but decreases of 1% for RCP4.5 and 20% with RCP2.6 relative to the baseline (1986–2005). With the integrated soil-crop management option, changes in WUE were −4% for RCP2.6, +9% with RCP4.5, and + 7% under RCP8.5. Assuming a high use of mineral fertilizer, the average increase in the predicted WUE with RCP2.6, 4.5, and 8.5 was 2%, 17%, and 13% over the historical runs, respectively (Fig. 8a).

Under the projected climate change, CROPGRO-Cotton predicted 7%, 22%, and 24% increases in N-PFP with the integrated soil-crop management practice and 14%, 30%, and 31% increases with the high mineral fertilizer use for RCPs 2.6, 4.5, and 8.5, respectively (Fig. 8b). Under un-amended conditions, CROPGRO-Cotton predicted changes in N-IE by −1% (RCP2.6), +0.2% (RCP4.5), and −4% (RCP8.5). With integrated soil-crop management practice, CROPGRO-Cotton predicted 2% and 5% increases in N-IE for RCP 2.6 and RCP4.5, respectively, but a decrease of 7% with RCP 8.5. The N-IE was projected to change by +8% with RCP2.6, +11% for RCP4.5, and −2% under RCP8.5 assuming the high mineral fertilizer use option (Fig. 8c).

3.4.3. Changes in seasonal N uptake

Under all future climate scenarios assumed, CROPGRO-Cotton predicted the largest increases in seasonal N uptake under RCP8.5 (Fig. 9). Under both the integrated soil-crop management option and the high use of mineral fertilizer, the predicted increases in N uptake were about 6, 17, and 33% under RCPs 2.6, 4.5, and 8.5, respectively. In soils without any amendment (CONT), N uptake is expected to improve by 46% under RCP8.5 and by 14% under RCP4.5, but to decrease by 7%

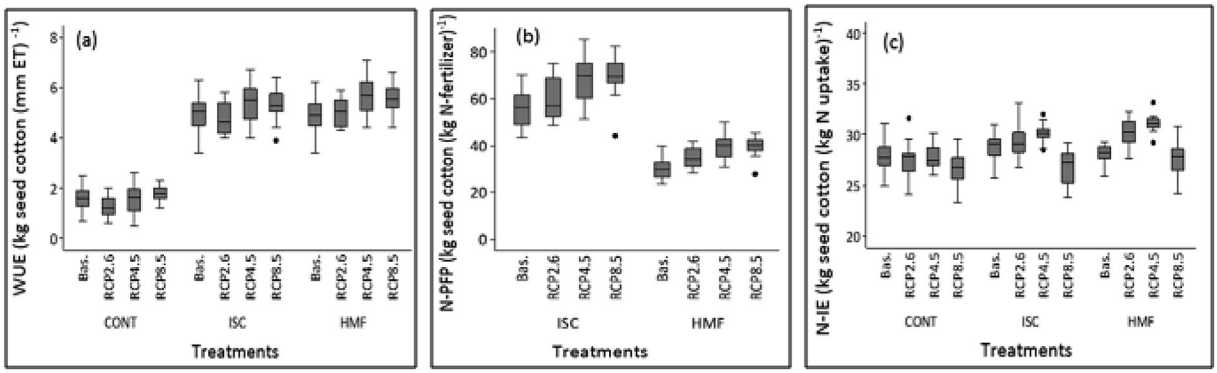

Fig. 8. Simulated changes in water- use efficiency (WUE, a), partial factor productivity (N-PFP, b), and nitrogen- internal use efficiency (N-IE, c) of cotton under an un-amended soil as control (CONT), integrated soil-crop management (ISC), and high mineral fertilizer use (HMF), while considering historical (Bas., 1986–2005) and future climate (2080–2099) under the assumptions of RCPs 2.6, 4.5, and 8.5.

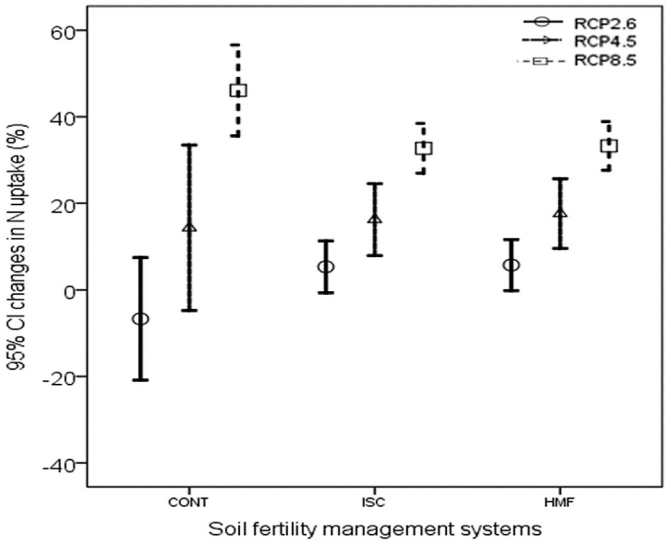

Fig. 9. Confidence intervals (CI, 95%) of changes in seasonal nitrogen uptake by cotton under the assumed future (2080–2099) climate scenarios of RCPs, 2.6, 4.5, and 8.5 relative to the historical uptake means (1986–2005) considering three fertility management levels (an un-amended control (CONT), integrated soil-crop management (ISC), and high mineral fertilizer use (HMF)).

under RCP2.6 (Fig. 9).

3.4.4. Variation in biomass and seed cotton yields

The CROPGRO-Cotton simulations showed significant variability in biomass and seed cotton yields between years under the historic and projected climate (Fig. 10). Under the assumed future climate scenarios of RCP4.5 and 8.5, and irrespective of the soil fertility options, the cumulative probability function showed a consistent enhancement of biomass (Fig. 10A1, 2, 3) and seed-cotton yields (Fig. 10B1, 2, 3) relative to the simulated historical baseline conditions. The CROPGRO-Cotton model predicted decreases in biomass (−9%) as well as of seed-cotton yields (−7%) under RCP2.6 as compared to the historical runs in an un-amended soil (Fig. 10A1, B1). However, substantial increases in biomass and seed-cotton yields were predicted without fertilization that would reach 14% and 15% under RCP4.5 and 44% and 41% with RCP8.5, respectively. When assuming the integrated soil-crop management or high mineral fertilizer use, the predicted enhancements were within 8–28% for biomass yield and 7–31% for seed-cotton yield across RCPs2.6, RCP4.5, and 8.5.

4. Discussion

Under the projected climate change in West Africa, adequate soil fertility management practices are more needed than ever to ensure an efficient and sustainable response of cotton, which is an important cash crop in this region. The CROPGRO-Cotton model was parameterized and evaluated for modeling growth, seed-cotton yield, soil moisture dynamics, and N uptake by cotton grown under different production systems and current weather conditions of the dry savanna in northern Benin. The evaluated model was applied for the first time in this region to determine optimum planting dates of cotton and in turn assess responses of cotton to different fertility management strategies under historical and future climate conditions.

The evaluation of the CROPGRO-Cotton model for the dry savanna conditions in Benin showed that the model simulated reasonably well anthesis, physiological maturity, final biomass accrual, and seed-cotton yield, whilst in-season biomass dynamics were generally underestimated. Since CROPGRO-Cotton does not simulate a decline in aerial biomass, the under-predicted patterns of aboveground biomass accumulation of cotton late in the season is likely due to the uncertainty in the parameterization of leaf area (Pathak et al., 2012).

In-season soil water dynamics and N uptake generally fitted the observed values. Similarly, a satisfactory CROPGRO-Cotton performance was reported for phenology and yields in Burkina Faso (Soler et al., 2011) and Cameroon (Gérardeaux et al., 2013). A satisfactory agreement between measured and predicted soil water content was previously reported by Gérardeaux et al. (2013) for the periods of 0–30 and 30–60 days after planting cotton. The deviations between simulated and measured soil water contents in deeper layers (Fig. 1), particularly under rainfed conditions, are likely caused by an inadequate modeling of root activities by CROPGRO-Cotton.

The results of the simulations by CROPGRO-Cotton under varying planting dates of the late flowering cultivar (H-279-1) were, as expected, better for early planting conditions (Sekloka et al., 2008). The model predicted yield losses of as much as 94 to 278 kg ha^{-1} per week of delay, confirming a similar range of losses (150 to 200 kg ha^{-1} per week of delay) reported by Lançon et al. (1989, 2007) for the region when planting cotton between mid to late July. The CROPGRO-Cotton model predictions indicated that a seeding of cotton in June seems optimal to gain the highest seed cotton yields especially in combination with mineral fertilizer use or an integrated soil-crop management.

The CROPGRO-Cotton model predicted initial increases in biomass accrual of cotton under the projected climate change. This increase is likely caused by the combined effects of increased CO_2 levels and air temperatures on biomass productivity as repeatedly reported for cotton varieties in controlled field experiments (Kimball and Mauney, 1993; Mauney et al., 1994; Reddy et al., 1995). Such responses of cotton have been explained by a combination of factors such as a reduction in canopy transpiration, increased photosynthesis, and water-use efficiency (Hatfield et al., 2011; Mauney et al., 1994; Reddy et al., 1995). CROPGRO-Cotton seems thus able to capture these underlying processes as reflected in enhanced WUE, albeit predominantly for RCP4.5 and 8.5. However, the decrease in biomass and WUE in an un-amended soil with RCP2.6 suggested that soil N deficits constrained the response of cotton to changing CO_2 levels (Rogers et al., 1993). The predicted sharp decline in biomass accrual after the vegetative growth stage seems to be caused by the impact of high temperatures on boll set and growth under elevated CO_2 (Reddy et al., 1999).

The model predicted higher WUE under RCP4.5 and 8.5 compared to RCP2.6, irrespective of the soil fertility management options assumed. This underscored on the one hand the postulated positive effects of CO_2 enrichment on cotton WUE since, reportedly, elevated CO_2 levels enhance photosynthesis and improve WUE by decreasing stomatal conductance and transpiration per unit leaf area (Adhikari et al., 2016). When assuming both historical and future climate conditions, the findings showed that the use of inorganic and organic fertilization, or combinations thereof, were likely to increase cotton WUE compared to the un-amended treatment. This difference in predicted water use response of cotton is mirrored in increases in seed cotton yield with both an integrated soil-crop management and high use of mineral fertilizer compared to un-amended soil treatment with similar rainfall. Hatfield et al. (2001) reported that management practices that increase plant N and phosphorus (P) nutrition have an indirect effect on water use through the physiological efficiency of the plant. However, the version of CROPGRO-Cotton used was not yet responsive to P (Hoogenboom et al., 2015). Since P remains one of the most limiting factors for agricultural production in various parts of West Africa (Bationo et al., 2012; Buerkert et al., 1996), users and planners would benefit when the model would be able to account for soil- and plant-P dynamics as well. Such improvements of CROPGRO-Cotton are relevant also because the stimulatory effects of elevated atmospheric CO_2 levels may be greatly reduced in P-stress environments (Singh et al., 2013).

The projected climate change for the region is likely to increase the efficiency of applied N-fertilizer as previously reported for controlled field experiments (Prior et al., 1998). Although an increased soil fertilization sustained N-use efficiency of cotton, only the integrated soil-

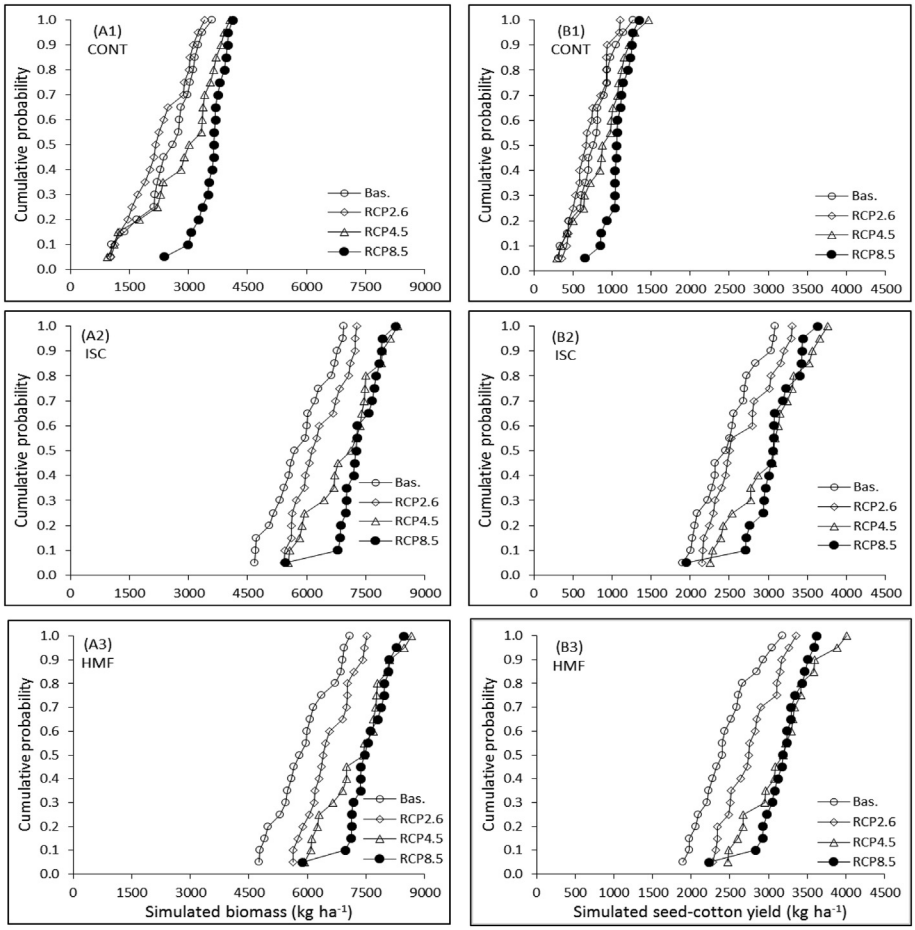

Fig. 10. Predicted aboveground cotton biomass (A) and seed cotton yields (B) as impacted by an un-amended soil control (CONT), integrated soil-crop management (ISC), and high mineral fertilizer use (HMF) under a historic climate (Bas., 1986–2005) and future climate (2080–2099) and while considering RCPs 2.6, 4.5, and 8.5.

crop management emerged as the most efficient nutrient use option under both historical and future climate conditions. This is due very likely to the partial substitution of nutrients by crop residue when using the integrated soil-crop management option compared to the high mineral fertilizer use alone as previously postulated (Amouzou et al., 2018a; Tao et al., 2017), although based on empirical findings on cotton productivity and nutrient use efficiency only. The downward trend of N-internal utilization efficiencies under RCP 8.5 resulted from the enhanced biomass accrual with a concomitant decrease in plant N concentration, typically known as the "dilution effect" (Loladze, 2002; Yuan and Chen, 2015) in response to elevated CO_2, which occurs regardless of the overall enhanced seasonal N-uptake (Prior et al., 1998; Singh et al., 2013).

The significant increases predicted for N uptake by cotton under the projected climate suggested that latent increases will occur at the expense of soil fertility and points at a further soil mining unless the increased demand for nutrient is met. Moreover, since N stress moderates CO_2 fertilization effects (Boote et al., 2011), further and greater attention is needed to arresting the current and continuously on going soil-nutrient mining during current cotton production (Amouzou et al., 2018a; Pieri, 1992; Stoorvogel et al., 1993). Under such business-as-usual scenarios, significant yield depressions are likely for cotton, which hence must be considered when designing soil fertility management options to counterbalance the soil fertility depletion in future cotton production systems.

On the other hand, the simulations showed that the predicted changes in climate will positively affect seed-cotton yield, most probably driven interactively by elevated atmospheric CO_2 levels, increasing temperatures, and rainfall variability. Similar to the findings reported here, an increase of seed cotton by 1.3 kg ha^{-1} year^{-1} was predicted due to the positive effects of CO_2 enrichment in northern Cameroon (Gérardeaux et al., 2013). Adhikari et al. (2016) simulated an enhancement of seed-cotton yield by 14–29% in the Texas high plains (USA), also assuming a climate change scenario with elevated CO_2 concentrations. In contrast, Reddy et al. (2002) using the GOSSYM crop model simulated a decrease of 9% in cotton yield in the Mississippi Delta, USA, when considering all projected climatic variables. Hatfield et al. (2011) reviewed free atmospheric CO_2 enrichment experiments and reported an increase of 36% for biomass and 44% for seed cotton in response to a doubling in CO_2 concentration.

Under both historical and future climate conditions, the cumulative probability function of seed-cotton yield (Fig. 10) showed considerable year-to-year variability underscoring thus significant effects of changes in climatic parameters in general, but in particular rainfall. The model was sensitive to the variability and changes in temperatures as evidenced by the different simulation results under historical and future climate conditions (Fig. 10). However, the model does not consider yet effects of canopy temperatures, which are usually "cooler" than air temperatures (Adhikari et al., 2016; McKenney and Rosenberg, 1993). Accounting for canopy temperatures instead of air temperatures, as presently is the case with the CROPGRO-Cotton model, will most likely increase the accuracy of simulating effects of transpiration influences (Webber et al., 2016, 2017).

The significant enhancement of cotton yields even without soil amendments is due to climatic changes that occur, however concurrently at the expense of soil nutrient depletion and thus may worsen on-going soil mining (Stoorvogel et al., 1993; Stoorvogel and Smaling, 1990). This is evidenced e.g. by the larger increases in N-uptake across

the soil fertility management options tested when assuming the medium and high GHG forcing scenarios. As fertilization usually is an integrated part of cotton cultivation in West Africa, the projected climate change for the region will likely improve overall cotton productivity in the Dry Savanna region when the application of nutrient is ensured. This is in sharp contrast with the severe decreases predicted for cereals, particularly maize and sorghum (Guan et al., 2017; Roudier et al., 2011; Sultan et al., 2013). The physiological effects of elevated CO_2 levels were postulated to be larger with the C3-plant cotton than for maize and sorghum, which are both C4-plants. The differential response of crops to enriched CO_2 environments has been frequently reported, albeit predominantly under controlled environments (Kimball and Mauney, 1993; Leakey, 2009; Mauney et al., 1994; Poorter, 1993; Reddy et al., 1995). Definitely, an increase in soil fertility is indispensable to sustain higher seed-cotton yields in the future (Fig. 10). On the other hand, cotton would, under such conditions, respond more efficiently to N fertilization when subjected to a sustainable management practice (Fig. 8).

5. Conclusions

The parameterized CSM-CROPGRO-Cotton model was capable of predicting accurately growth and development, in-season soil water dynamics and N-uptake, and final yields of cotton under Dry Savanna conditions of West Africa. Climate change will likely increase water- and N- use efficiencies and yields of cotton, at least when assuming a high use of mineral fertilizer or an integrated soil-crop management practice. Given that the tested fertilizers levels were almost double the current recommendations for cotton, it seems necessary to update the current soil fertilization recommendation for this crop in the dry savanna region of Benin. This is needed also to benefit effectively from the positive effects of the projected climate change and thus keep pace with the highly needed sustainability of cotton production systems.

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Appendix A. Description of experimental treatments, design and management practices in the three field experiments carried out at Ouri Ouri Yori, North Benin during the 2014 and 2015 cropping seasons

Designations	Experiment 1	Experiment 2*	Experiment 3
Treatments	High use of mineral fertilizer (HMF)	Un-amended soil as control (CONT), and integrated soil-crop (ISC)	Low external input (LEI)
Exp. design	Randomized complete block design (RCBD)	RCBD	RCBD
Replications	3	3	3 farmers per cropping system
Plots size	6 m × 5 m	7 m × 4.2 m	0.5–1.5 ha
Test crops	Maize, sorghum and cotton	Maize, sorghum and cotton	Maize, sorghum, and cotton
Soil type	Gleyic Alisols	Gleyic Alisols	Alisols, Plinthosols, Luvisols
Planting dates	Season 2014: July 19th	Season 2014: July 4th	Season 2014: July 18th–31st
	Season 2015: June 23th	Season 2015: June 25th	Season 2015: June 23rd–July 25th
Planting scheme	For maize and sorghum: − 80 cm × 40 cm For cotton: − 80 cm × 30 cm	For maize and sorghum: − 80 cm × 40 cm For cotton: − 80 cm × 30 cm	For each main crop 70–80 cm × 40–50 cm
Density at seeding	For maize and sorghum: − 6 plants m^{-2} For cotton: − 8 plants m^{-2}	For maize and sorghum: 6 plants m^{-2} For cotton: 8 plants m^{-2}	5–7 plants m^{-2}
Fertilizer rates	80 kg N ha^{-1}, 26 kg P ha^{-1}, and 30 kg K ha^{-1}	CONT: no fertilizers; ISC: 44 kg N ha^{-1}, 15 kg P ha^{-1}, and 17.5 kg K ha^{-1} + residues retention	Different rates according to farmers
Type of Fertilizers used	*For maize and sorghum*: Urea (46%), Triple superphosphate (TSP, 46% P_2O_5), and Potassium Chloride (60% K_2O) *For Cotton*:, $N_{14}P_{23}K_{14}S_5B_1$, Urea, TSP, Potassium Chloride	*For maize and sorghum*: Urea, TSP, Potassium Chloride *For Cotton*: $N_{14}P_{23}K_{14}S_5B_1$, Urea, TSP, Potassium Chloride	*For maize and cotton*: $N_{14}P_{23}K_{14}S_5B_1$ and urea

Fertilizer application dates	First application: - Season 2014: 20 days after planting (DAP) - Season 2015:21 DAP - Second application: - Season 2014: 45 DAP - Season 2015: 44 DAP	First application - Season 2014: 21 DAP - Season 2015: 21 DAP Second application: - Season 2014: 40 DAP - Season 2015: 44 DAP	First application: - Both season: about three weeks after planting Second application: - Both season: about three weeks after the first application
Weeding	Regularly weeded manually	Regularly weeded manually	Weeded twice in each season
Net plot	4 m × 2 m	4 m × 2 m	4 m × 2 m, 3 replications per plot

Source: (Amouzou et al., 2018a).

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